

Aeroelasticity of a Helicopter Blade Using the Euler Equations

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Introduction

ACCURATE aeroelastic computations of helicopter rotor blades involve the use of high-fidelity fluids and structure models. Computing the flows that are dominated by shocks, waves, and blade–vortex interactions requires the use of three-dimensional (3-D) Euler/Navier–Stokes (ENS) equations [1]. Because using the Navier–Stokes equations is computationally very expensive [1], the significantly less-expensive 3-D Euler (3DE) equations can be used for preliminary assessment of flow complexities such as shock waves and vortices. Reference [2] presented the first 3-D transonic aeroelastic computation of its kind for fixed wings by time-accurately (TA) coupling the Euler flow equations of motion with the modal structural equations of motion. The work in [2] was based on the success of the original effort to TA couple 2-D unsteady potential flow equations with structural equations, as reported in [3]. The current practice for aeroelastic computations of rotorcraft involves using precomputed displacements from rotorcraft comprehensive analysis methods [4] and iteratively correcting them in ad hoc fashion using loads from ENS or 3DE equations. Comprehensive analysis uses dependent parameters, such as measured thrust and aerodynamic lookup tables, to adjust the control angles for ENS computations [5]. The hybrid approach of combining comprehensive analysis with ENS/3DE, known as either loose coupling or delta coupling [4,5], is not mathematically valid [6], and it is not a correct procedure for time-dependent cases such as rotating blades [7].

The objective of this Note is to demonstrate the use of time-accurate procedures for computing the aeroelasticity of rotating blades in contrast with using existing hybrid methods. The aeroelastic responses are computed by TA integrating flow and structural equations following the procedure presented in [8]. Only independent flight parameters such as rotating speed, shaft angle, and control angles are used as input. This approach does not involve any tuning of the input parameters using lookup tables. Results are demonstrated for the isolated single blade of a UH-60A helicopter [9]. Fourier analysis is applied to compare data with flight tests.

Approach

The solution approach is based on the modal form of Lagrange's equations of motion. From modal analysis, the displacement vector $\{d\}$ can be expressed as

$$\{d\} = [\psi]\{q\} \quad (1)$$

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where $[\psi]$ is the modal matrix and $\{q\}$ is the generalized displacement vector. The final matrix form of the aeroelastic equations of motion is

$$[M]\{\ddot{q}\} + [G]\{\dot{q}\} + [K]\{q\} = \{F\} \quad (2)$$

where $[M]$, $[G]$, and $[K]$ are modal mass, damping, and stiffness matrices, respectively. $\{F\}$ is the generalized aerodynamics force vector defined as $\frac{1}{2}\rho U^2[\psi]^T[A]\{C_p\}$, where $[A]$ is the diagonal area matrix of the aerodynamic control points, ρ is the freestream density, and U is the local speed of the blade section. The aerodynamic unsteady pressure vector $\{C_p\}$ is computed by solving 3DE equations.

Equation (2) is solved using RUNEXE, a modular C++ based process to couple flow and structural codes [8], as well as the Newmark explicit time integration method [10]. The data are accurately transferred from the flow solver to the structure's solver using the area-coordinate approach [11].

Validation

The single blade of the UH-60A helicopter, with its extensive set of flight data [9], is selected for demonstrating the results of the approach described. The blade shown in Fig. 1 has a radius of 8.18 m and a chord of 0.53 m, with a swept tip at a 92.9% radial station. A C-H grid topology with 151 streamwise, 45 spanwise, and 40 normal direction grid points is used. In [8], it is shown that this grid topology is adequate to model subsonic and transonic flow regimes for isolated blades using the Euler equations. The blade surface is represented by a total of 3600 grid points. Selected for demonstration is the high-speed test case C8534 [9], which corresponds to a freestream Mach number of 0.236 with an advance ratio of 0.37, a tip Mach number of 0.642, and a blade rotation speed of 4.3 Hz. The structural modal data for the first bending, torsion, and lead–lag motions are defined using measured data [12].

The time-accurate computations are made by using a constant time step for the Euler flow equations of motion, which are solved using the Beam–Warming implicit time integration method [13]. First, computations are started with 720 steps per revolution; then, they are repeated with an increasing number of steps per revolution (NSPR) until the responses converge. The time step for integrating the Lagrange equations of motion is computed using the time step used for the Euler equations. The explicit time integration method [14] based on the linear acceleration assumption [2,3] is found to be adequate, since the time step required for the flow solver is orders of magnitude smaller than that for structures.

It is observed that the time-consuming staggered time-step approach [15,16], which needs additional bookkeeping of data transfers, is not needed. It is also noted that, in recent literature [17], the time-accurate explicit time integration method [10] used here and in [2,3] is wrongly classified as a non-time-accurate loose-coupling approach. An alternate approach [18] for computing aeroelasticity using the 2-D Euler equations, similar to the previous approach presented using potential equations [3], was recently published but lacks independent validation with existing experiments, such as for the NACA64010 airfoil reported in [2].

Convergence is monitored by tracking the normal force coefficient ($M^2 C_n$, where M = local Mach number) at a 86.5% radial station when the blade is at 30 deg azimuth. It requires about three revolutions for the aeroelastic responses to reach a periodic motion. This calculation is repeated by increasing the NSPR in increments of 720. Figure 2 shows convergence of air loads at an 86.5% span for a 30 deg azimuth of the fourth revolution. Aeroelastic responses converge at NSPR = 3600. This is verified by using NSPR = 4320, which produces results nearly identical to NSPR = 3600.

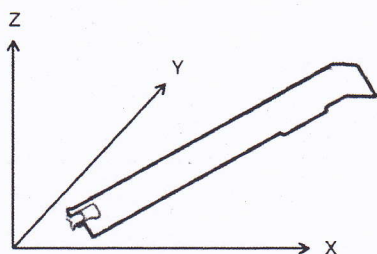


Fig. 1 Isolated single-blade configuration.

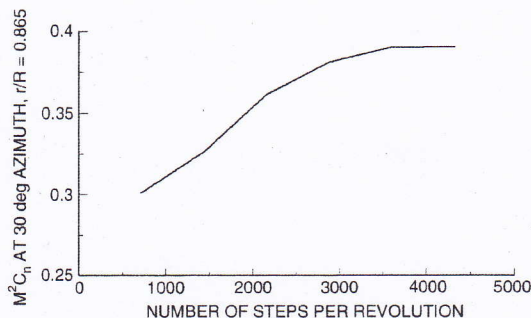


Fig. 2 Convergence of sectional lift coefficient.

Figure 3 shows a comparison of the tip twist aeroelastic responses between the computed and measured loads. Corresponding results for the sectional pitching moment at an 86.5% radial station are shown in Fig. 4. As shown in Figs. 3 and 4, about one revolution is required for the initial transients to disappear, and results reach periodic motion within the third revolution. Responses reach peak at around 90 deg azimuth since the local effective Mach number due to combination of forward speed and blade rotation is maximum. The

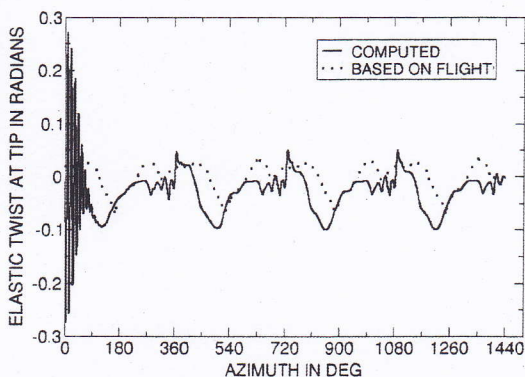


Fig. 3 Comparison of aeroelastic response of tip twist.

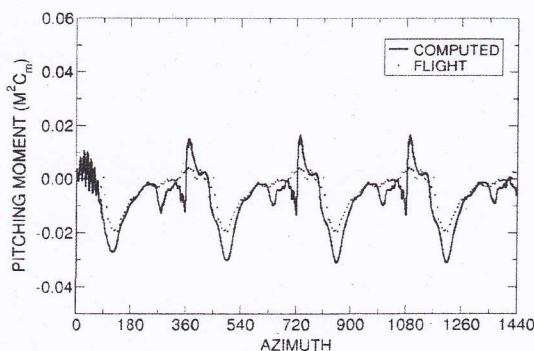


Fig. 4 Sectional pitching moment responses.

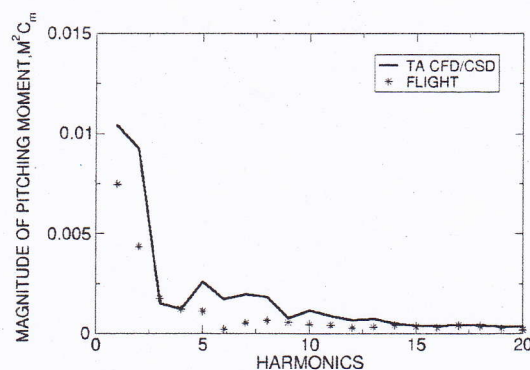


Fig. 5 Comparison of pitching moment magnitudes at the 86.5% radial station. CFD denotes computational fluid dynamics, and CSD denotes computational structural dynamics.

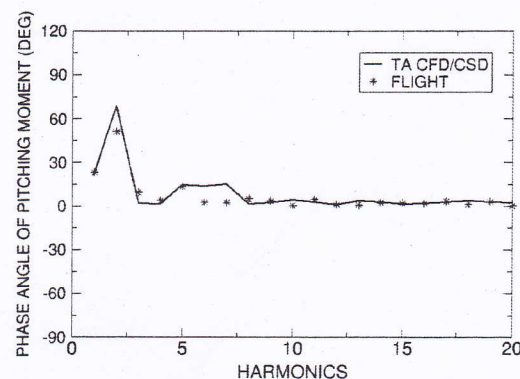


Fig. 6 Comparison of pitching moment phase angles at the 86.5% radial station.

information in the experiment is not adequate to explain the phase difference between computed and measured data. The computed tip displacements and sectional loads are higher than measured values. With the given limited public-domain structural data for the UH60-A blade, these results are acceptable.

To further analyze the results, Fourier transformations are applied to the computed and measured airloads. Comparison of data by using Fourier coefficients eliminates the process of comparing the time responses by removing the mean in an ad hoc fashion [4] to accommodate the lack of information (such as start time of responses) from the measured data. Magnitudes and phase angles with respect to the azimuth of the blade are computed for 20 harmonics. Figure 5 shows the comparison between the magnitudes of the computed and flight pitching moment ($M^2 C_m$) at an 86.5% radial station. The magnitudes become small after the ninth harmonic. Comparisons between computed and measured data are good for the magnitude of all 20 harmonics. Figure 6 shows the corresponding comparison of phase angle scaled by the ratio of current magnitude to the magnitude of the first harmonic. The results are scaled to eliminate any noise that may exist in the measured and computed data at small amplitudes. The plot shows a good comparison for all harmonics.

Conclusions

Aeroelastic computations are made for a rotating blade by time-accurately integrating the Euler flow equations with the modal structural equations. Contrary to current practice, it is shown that the computations can be made without arbitrarily tuning the results using low-fidelity lookup tables for aerodynamic data. Only primitive inputs are used from the flight measurements. Results computed for an isolated, single blade compare reasonably well with the flight data. It is shown that the linear acceleration-based explicit time integration approach is adequate to integrate the Euler flow equations with the

modal structural equations without warranting the use of the expensive staggered approach used elsewhere. Further improvements can be made by modeling the multiblade system and by using detailed 3-D modal data from a shake test that includes root multibody dynamics.

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